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A COMPUTATIONAL MODEL OF THE PERFORATION OF MULTI-LAYER METALLIC LAMINATES

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R.L. WOODWARD AND I.G. CROUCH

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ABSTRACT

A model for the deformation of multi-layer metallic laminate targets during ballistic impact is described. The model divides the process into a stage of plug acceleration followed by dishing of the rear of the target, and allows for the effects of variable interlamellar bend strength. A computational procedure is described, as well as the mechanical test procedures to generate the input data for the program. Examples of the application of the model are described to illustrate the interpretation of results, the limitations of the model, and the use of the model is parametric studies for laminate design. The computer program is listed with typical input and output data.

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CONTENTS

A COMPUTATIONAL MODEL OF THE PERFORATION OF MULTI-LAYER METALLIC LAMINATES

1. INTRODUCTION

Computation of ballistic impact events can be via simple analytical equations, more complex analytical models requiring computational procedures, or by finite element or finite difference computer codes. Whilst the computer codes have been partially successful in providing an impressive graphic output of stages in the perforation process, they have not been able to effectively provide a means of calculating the result of ballistic impact events. The analytical equations and procedures have provided the main tool for efficient parametric studies and basic insight into the mechanics of perforation, provided the scope of the problem was well defined. A number of such analytical procedures have been developed and documented in MRL work [1-4], and it has been shown that an understanding of the mechanics allows the methods to provide good approximate answers to a range of problems [4].

In recent work Woodward and Crouch [4] demonstrated how approximate calculations could be performed on simple two layer laminates by inserting small modifications in an earlier plugging failure model [1]. In the present work the same general approach is used with experimental observations on the behaviour of multi-layer metallic laminates to develop a model for perforation of such laminates. The step from homogeneous metals to laminates also required the development of suitable test procedures designed to provide appropriate materials input data.

2. PERFORATION MODEL

For practical purposes the number of layers in the metallic laminates is defined as the number of layers of metal, so that any adhesive or fibre reinforcement is considered as part of this unit. The thickness of a layer is then the total

thickness divided by the number of metal layers, and the approach assumes all layers are equivalent. The problem to be considered assumes a non-deforming projectile.

The perforation process is divided into two stages as illustrated schematically in Fig. 1. When the projectile impacts the target the velocity difference ensures an initial stage of acceleration of material in front of the projectile. During the time in which the plug is accelerated, the reaction force slows the projectile so that a stage is reached after which projectile and plug move at the same velocity. In a homogeneous metal target, shearing between the plug and the target would then lead to fracture and separation of the plug. In a laminate, on the other hand, the difficulty of crack propagation across a number of laminae, combined with the ease of separation by a crack travelling along the bond ensures that the second stage of perforation involves delamination and dishing failure of the rear of the target as illustrated in Fig. 1(c). This second stage must involve an integral number of layers as it is assumed that the bonding between lamina is weak compared to the metal strength.

(a) Stage I - Plug Acceleration

The method follows generally the procedure described by Woodward and de Morton [1] with modifications allowing adaption to composite materials for which flow rules have not been universally established. The uniaxial stress and uniaxial strain data from a constrained compression test on the composite, described in Section 3, are curve fit to the form

$$\sigma = \sigma_1 \epsilon^{\eta_1}, \quad \epsilon \leq \epsilon_0 \tag{1a}$$

$$\sigma = \sigma_2 \epsilon^{\eta_2}, \quad \epsilon > \epsilon_0 \tag{1b}$$

where σ is the normal stress on a punch in the constrained compression test,
ϵ is the uniaxial strain,
σ_1, σ_2, η_1, η_2 and ϵ_0 are curve fitting constants for data.

The use of two curves separated at a strain ϵ_0 allows considerable flexibility in covering a wide range of material behaviour. The elastic phase of loading is not explicitly separated as this leads to an insignificant change in the result. The assumed uniform velocity of a plug moving ahead of the projectile is obtained by integration of the wave equation

$$\Delta v = \frac{\Delta \sigma}{\rho c} \tag{2}$$

where Δv is a velocity increment associated with a stress gradient $\Delta\sigma$ and ρ and c are the material density and wave velocity respectively.

This plug velocity, V_1, becomes

$$V_1 = \left(\frac{\eta_1 \sigma_1}{\rho}\right)^{1/2} \frac{2}{\eta_1 + 1} \epsilon^{(\eta_1 + 1)/2} , \quad \epsilon \leq \epsilon_o \qquad (3a)$$

and

$$V_1 = \left(\frac{\eta_1 \sigma_1}{\rho}\right)^{1/2} \frac{2}{\eta_1 + 1} \epsilon_o^{(\eta_1 + 1)/2} + \left(\frac{\eta_2 \sigma_2}{\rho}\right)^{1/2} \frac{2}{\eta_2 + 1} \left(\epsilon^{(\eta_2 + 1)/2} - \epsilon_o^{(\eta_2 + 1)/2}\right), \quad \epsilon > \epsilon_o \qquad (3b)$$

The normal force F on the plug of diameter D is given by

$$F = \frac{\pi}{4} D^2 \sigma_1 \epsilon^{\eta_2} , \quad \epsilon \leq \epsilon_o \qquad (4a)$$

$$F = \frac{\pi}{4} D^2 \sigma_2 \epsilon^{\eta_2} , \quad \epsilon > \epsilon_o \qquad (4b)$$

When the back of the plug moves a distance ΔL_B an increment of work ΔW_N is done where

$$\Delta W_N = F \, \Delta L_B \qquad (5)$$

At the strain ϵ, the plug height is

$$h = h_o \exp(-\epsilon) \qquad (6)$$

where h_o is the initial laminate thickness.

The situation at the end of stage I is illustrated in Fig. 2(a) which relates the displacement of the back of the plug, L_B, the front of the plug, L_F, the residual contact length, L_C, and the initial, h_o, and final, h, plug thicknesses to both the geometry used in the plugging solution of Woodward and de Morton [1] and the shearing of the laminae in the present instant. The following relations follow directly from the earlier plugging model [1].

$$t = 2(h_o - h)/V_o \qquad (7)$$

where t is the time for stage I and
V_o is the projectile impact velocity.

$$L_F = V_1 t/2 \tag{8}$$

$$L_B = (V_o + V_1)t/2 \tag{9}$$

The work done in shear, W_S, in stage I is given by

$$W_S = \pi D \tau_s \{h(h_o - h) + L_F(2h - L_F)\} \tag{10}$$

where τ_s is the shear strength of the laminate. The work done in friction between the projectile and the laminate, W_F, is

$$W_F = \pi D \tau_s L_B^2/2 \tag{11}$$

The new projectile velocity, V_p, at the end of stage I is given by

$$V_p = \{V_o^2 - 2(W_N + W_S + W_F)/m\}^{1/2} \tag{12}$$

where m is the projectile mass.

The computational procedure increments strain in the plug in stages, calculating new values of V_1 (plug velocity) and V_p (projectile velocity) until a value is found at which the work done is sufficient for V_p to equal V_1. At this stage we have a situation where projectile and plug are moving together and we proceed to stage II.

(b) Stage II - Dishing Failure

For a homogeneous plate where plugging failure is observed, Woodward and de Morton [1] used a shearing failure mode for exit of the plug. For the laminates, some mechanism which allows dishing and stretching is desirable, and for the particular case of flat ended projectiles plug separation as well. Two decisions need to be made, viz. how many laminae remain to be perforated after stage I, and which model to use to calculate the work done.

Examination of a number of sectioned partly perforated samples was used to try and establish a criterion for which laminae were sheared through to failure, and which remained intact. It was generally observed that significant shear displacements, greater than a layer thickness, are possible

without separation occurring. In addition shear zone widths vary from material to material with the distinction between shearing and bending deformation becoming one of judgement in many cases. Thus a simple displacement or shear strain criterion for failure was not seen to be possible at this stage. Based on observations it was decided to pragmatically locate the back of the plug at the end of stage I, defined by L_B and the next interface below this point as the one at which separation occurred, as illustrated in Fig. 2(a) and (b). This approach concurred well with what was observed in most accompanying experiments and the ballistic limit predictions were reasonable.

For a model of deformation in stage II the structural approach of Woodward [3] appears ideal as it allows dishing, stretching and plugging deformations. Unfortunately the assumptions of that model apply only in the case of thin targets where projectile radius is greater than the target thickness, and when the target thickness increases beyond this the model produces large errors. For many problems of the type being considered in the present instant it was observed that after the first stage, the thickness still to be penetrated was generally of the order of one projectile diameter, thus the use of the structural model is not possible. There are no other models which treat all aspects of the deformation and which at the same time do not require ballistic experiments to generate some of the input deformation. For many blunt projectile impact problems it has been found [3] that a simple analytical equation for dishing failure which allows for bending and stretching failure only of the plate gives good estimates of the work done. This model was originally derived by Taylor [5] and Thomson [6] and modified by Woodward [7] to include the effect of plate bending. The work, W_D, is given in terms of the thickness T_E to be penetrated in stage II, Fig. 2(a), and the material strength, Y, by

$$W = \pi D Y T_E (D + \pi T_E)/8 \qquad (13)$$

where the first term represents the stretching work and the second term the work done in bending.

For want of a better approach this method of treating the dishing failure was adopted as it includes some of the observed features and should calculate the work done to a reasonable approximation. Whilst it copes with these aspects it must be accepted that it may not be able to distinguish differences in performance which result from small changes in failure mode. To cope with the differences in bend properties of a laminate and a homogeneous metal and account somewhat for interlamellar bond strength effects, equation (13) was modified to accept appropriate laminate strength terms.

If there are n layers to be perforated and the layer thickness is T_L, then the tension or stretching work, W_T, in the second stage is

$$W_T = \pi D^2 \sigma_u n T_L/8 \qquad (14)$$

where σ_u is the ultimate tensile strength of the laminate measured in a tension test.

In bending the problem is likened to a beam of width πD bent through an angle
$\pi/2$. The beam is assumed to be fully plastic and σ_F is the fibre stress measured in a simple four point bend test. Then for an unbonded composite the work done in bending is

$$W_B = n\pi^2 \sigma_F D T_L^2/8 \tag{15}$$

For a bonded laminate bending is divided into stages before and after the bond breaks along the centreline at some angle of bend θ given by

$$\theta = \theta_c (h_o/nT_L)^2 \tag{16}$$

where θ_c is the angle at which the bond breaks in the simple four point bend test used in the original laminate of thickness h_o to determine σ_F.

The work done in bending for a bonded laminate is then given by the sum of the two terms

$$W_B = n^2 \pi \sigma_F D T_L^2 \theta/4 \tag{17a}$$

and $$W_B = (n_1^2 + n_2^2) \pi \sigma_F D T_L^2 (\frac{\pi}{2} - \theta)/4 \tag{17b}$$

where the integers n_1 and n_2 are defined by

$$n_1 + n_2 = n \tag{18a}$$

and $$|n_2 - n_1| \leq 1 \tag{18b}$$

which allows for the n to be uneven so that the laminate effectively breaks its adhesive bond along the nearest bondline to the centre.

The solution procedure is to take the kinetic energy of the projectile and plug from stage I, calculate the work done in stage II using equations (14) to (18) and compare these to determine whether or not the projectile perforates. The computer program to carry out the calculations was

written so that it increments the initial velocity in small steps until the projectile just perforates and this is treated as a prediction of the ballistic limit of the composite.

3. LAMINATE CHARACTERIZATION

Use of the above model requires materials data in a suitable form to treat plug compression and acceleration, shear strength, bending and tensile deformation. With the development of a better understanding of composite behaviour it may be possible to estimate these parameters from the properties of the component parts. For the present, a set of procedures has been developed which 'simulate' the deformations experienced in the ballistic impact as best possible, so that the data is appropriate, whilst the testing remains simple. Many of the parameters are combinations of basic strength data, such that experience with application to a number of composites may allow estimates of the parameters with far more limited testing programs in the future. Rate dependence of mechanical properties is not considered as the aluminium alloys used in the present work are insensitive to strain rate. There is however, no difficulty in including the effect of strain rate on strength properties in the analysis, if that data are available. The procedures are described below.

(a) Compressive Deformation

The compression of the plug during acceleration can be simulated by compression of a plate between two flat axially aligned punches, a constrained compression test. The subpress for carrying out such tests was described by Woodward and de Morton [1], and its application to laminates illustrated by Crouch and Woodward [8]. Typical uniaxial stress/uniaxial strain data from such a test is shown in Fig. 3(a) with a typical cross sectioned sample in Fig. 3(b). The data is easily fitted to curves of the form of equations (1) to obtain the materials parameters σ_1, η_1, σ_2, η_2 and ϵ_0, using straight lines on plots of logarithm of stress versus logarithm of strain.

(b) Shear Deformation

For shear deformation the laminate is assumed to approximate a rigid/plastic material with constant flow stress. A blanking test is carried out to produce a force displacement graph as in Fig. 4. The area under the curve is integrated up to a displacement equivalent to the laminate thickness. From the work done in shear, W_S, the punch diameter D, and the laminate thickness h_0, the shear stress for use in the program τ_s, becomes

$$\tau_s = 2 W_S / \pi D h_0^2 \qquad (19)$$

This is equivalent to assuming a load/displacement relation of constant slope with total work up to the displacement of the sample thickness equal to the actual work in the test as shown in Fig. 4.

(c) Bending Deformation

Figure 5 shows a set of typical moment/angle of bend curves obtained in four point bending. In the case of well bonded laminates, the lamina remained bonded to a very large bend angle. With "weak" bonding a discontinuity is observed in the moment/angle curves when bond failure occurs along the centreline of the laminate. Generally no further bond breakage was observed to very large bend angles, so beyond the discontinuity the sample can be considered as being made up of two pieces of multilayer laminate with no bond in the interface between the two. For unbonded laminates the bending moments were consistent with the bending of the sum of the individual layers of the laminate. Thus from the moment to which the curves extrapolate at high angles of bend, M_p, the fibre stress, σ_F, was determined from equations (20a) for good bonding, (20b) for "weak" bonding and (20c) for unbonded laminates.

$$\sigma_F = 4\ M_p / w\ h_o^2 \tag{20a}$$

$$\sigma_F = 8\ M_p / W\ w_o^2 \tag{20b}$$

$$\sigma_F = 4\ n\ M_p / w\ h_o^2 \tag{20c}$$

where w is the width of the sample used in the four point bend test.

The critical angle of bend at which the bond breaks in the four point bend test, θ_c, was also measured and used as a measure of the strength of the bond in the computations for the cases of "weak" bonding.

(d) Tensile Deformation

The parameter used for the tensile flow stress, σ_u, in equation (14) was the ultimate tensile strength measured in a tension test on the composite.

(e) Experimental Laminates

The construction and physical properties of laminates tested in the present study are given in Table I, and the input data for simulation, determined with the above testing procedures is given in Table II.

4. DISCUSSION

Many of the assumptions in the simplified model have been explicitly stated above. Three assumptions are based purely on practical approaches to observed behaviour, viz. the method used to estimate the number of layers still to be perforated at the end of stage I, the simplified method of including bond strength as measured in the bend test, and the use of a plug mass in stage II rather than the mass of a whole dished region as the latter is rather indeterminate. The treatment of stage II in terms of the simple analytical dishing model gives reasonable estimates of work done, however it will prevent the model distinguishing material differences which relate to the ductility of the plate as seen in the case of plug separation. It has been observed that the model predicts lower than expected ballistic limits with unbonded laminates when impacted by flat ended projectiles relative to bonded laminates. The difference in experiments is not generally that great and the discrepancy arises because the model attributes more work to the bending deformation of the bonded compared to the unbonded layers. In practice an unbonded laminate can show greater ductility in bending and this aspect is not part of the formulation.

What then is the application of the model? Table III presents observed and predicted ballistic limits for a range of laminates impacted by flat ended projectiles. The cases include variations in bond strength, the inclusion of Kevlar fibre reinforcement, different layer numbers and thicknesses of laminate as well as unbonded laminates. Generally the estimate of the ballistic limit is of the correct order of magnitude. In addition where conditions are similar the order of merit is correctly predicted in most cases. The model is seen to generally overestimate performance. Cases D1 and M1 illustrate the case of an unbonded laminate (D1) showing higher ballistic limit relative to the bonded laminate than expected because of greater ductility, despite the expected much higher ballistic limit in the bonded laminate (M1) which has a higher bond strength. The low ballistic limit in the case of M3 is associated with poor ductility leading to complete fracture separation of petals at the back of the plate. Figure 6 compares a section from a perforated laminate made from the 2090 alloy with a more ductile failure from a laminate of 2024 alloy and a typical six ply 7075 aluminium laminate.

The best correlations of experiment and prediction are for relative thicker laminates impacted by 7.5 mm fragment simulators reported by Simmons et al. [10] and shown as relative ballistic limit in Fig. 7. The better correlation may be related to the higher relative target thickness to projectile diameter ratio in this case, which ensures that the first stage of plug acceleration dominates the problem and this is where the model is more accurate. In addition with the smaller diameter projectile plugging is less significant and this is the aspect where the model poorly represents the simulation of behaviour. This type of problem, thick targets and small fragments, is the more usual and therefore the more useful application in

practice. In addition it represents the class of problem where organic composites, to which it may be possible to extend the approach, are usefully applied.

The model can thus be used with metallic laminates to estimate overall ballistic performance. It can also be used to study the effects of variations in laminate structure on expected performance, parametric studies, provided one is aware of how the limiting assumptions may influence the output. Thus a radical change in material type from a ductile to very brittle material or from a bonded to an unbonded laminate may result in changes which the model does not include. However, number of layers, bond strength, laminate thickness, projectile dimensions and some variations in alloy type are all parameters amenable to study. The model also gives a picture of the physics of the deformation and what are the appropriate properties to measure which will determine ballistic performance.

The computer program, LAMP, is listed in Appendix 1 with a typical input and output as well as a discussion of the output parameters. The program was written to estimate ballistic limits by incrementing the impact velocity in 5 ms^{-1} steps. The understanding of behaviour is not sufficient to place much value on an effort to predict output velocities above the ballistic limit using such a model, when this can be done as efficiently and effectively using other techniques [9]. The program stops and prints output parameters as soon as the ballistic limit is exceeded. In some cases the residual velocity predicted can be substantial as the small incremental velocity steps can result in a sudden change in one layer thickness to be perforated in stage II. This is as would be expected from such a model and does not make the predicted ballistic limit of any less value. What it does do is highlight the importance of the model being for multi-layers of which four is about the lower limit. A simple two layer structure can be handled by a simple procedure developed earlier [4]. By combining these tools one has a useful approach to studying the ballistic behaviour of laminates which should reduce considerably the requirement for ballistic testing. In addition the test procedures developed provide simple tools for studying those laminate deformation mechanisms of importance for ballistic performance.

5. CONCLUSION

The perforation of metallic laminates has been modelled by a two stage process of plug acceleration followed by dishing behaviour. Test procedures to determine laminate characteristics were outlined, and computations compared with empirical data for ballistic limits for a range of laminates. The model makes reasonable predictions of ballistic limit, however, its main use is shown to be as a tool for parametric studies of behaviour in relation to laminate design. Limitations in the application of the model relate to effects of bonding and material ductility on the ductile/brittle failure response, under impact conditions.

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Table I Metallic Laminates – Physical and Mechanical Properties

PROPERTY	L9	L12	L10	L28	D1	M1	M2	M3
	MATERIAL CODE							
Alloy	7075	7075	7075	7075	2024	2024	7075	2090
No. of Layers	6	6	6	6	4	4	6	4
Adhesive	HYSOL**	HYSOL	HYSOL	HYSOL	-	FM73	FM73	FM73
Kevlar Present? (Y/N)	N	Y	N	N	N	N	N	N
Total Thickness* (mm)	6.38	8.17	7.98	8.17	6.36	7.00	7.40	6.80
Lamine Thickness* (mm)	1.02	1.02	1.02	1.02	1.59	1.59	1.02	1.59
Mean Bond-line Thickness* (μm)	57	414	366	414	-	213	252	147
Vol Fraction, Alloy*	0.96	0.75	0.77	0.75	1.0	0.91	0.83	0.94
Areal Density† ($kg\ m^{-2}$)	17.14	19.43	18.90	19.21	17.81	18.00	18.58	17.02
Volume Density† ($kg\ m^{-3}$)	2687	2379	2385	2353	2800	2570	2511	2503
0.2% Proof St¶ (MPa)	483	407	387	377	355	322	418	494
UTS¶ (MPa)	540	511	433	422	595	473	466	517
% Elongation¶ (%)	≥12	~12	≥12	≥12	~13	≥13	≥12	≥9

Notes:
- * Typical values
- † Calculated values based upon known densities of constituents and typical values (*)
- ¶ Predicted values based on Rules of Mixture and assuming negligible tensile strength for adhesive
- ** Hysol EA9309.3 (NA)

Table II **Laminate Input Data for Use in Program "LAMP"**

	MATERIAL CODE						
	D1	M1	L9	L12	L28	M2	M3
Thickness (mm)	6.36	7.00	6.42	8.20	8.50	7.38	6.80
Density (kg m^{-3})	2800	2570	2690	2380	2310	2511	2503
σ_1 (MPa)	3020	3715	6920	13335	12302	8913	4753
n_1	0.34	0.43	0.55	0.82	0.88	0.66	0.42
ϵ_0	.05	.05	.05	.05	.05	.05	.05
σ_2 (MPa)	3020	2042	2570	2240	2820	2188	1875
n_2	0.34	0.29	0.21	0.214	0.38	0.20	0.11
τ_z (MPa)	180.0	188.	178.	166.	134.	164.	195.
σ_F (MPa)	332.	411.	516.	433.	445.	512.	536.
θ_c (°)	0.1	60	2	9	50	40	32
σ_u (MPa)	514	412	538	503	393	487	514

Table III **Terminal Ballistic Data for a Selection of Experimental Laminates**

Material Code	Material Type			V-50 Values (m/s)	
	No of plies	Alloy	Adhesive	Experimental	LAMP prediction
D1	4	2024	-	~200	235
M1	4	2024	FM73	~208	285
L9	6	7075	Hysol	210	285
L12	6	7075	Hysol + Kevlar	236	325
L28	6	7075	Hysol	273	305
M2	6	7075	FM73	~220	310
M3	4	2090	FM73	189	335

Note: Projectile : 12.7 mm diameter, 12.5 g hard-steel cylinder

APPENDIX

The program for computing the ballistic limit of metallic laminates is called LAMP. It takes input from the file LIMP.DAT and output is provided in a file LOMP.DAT. The program increments velocity in steps of 5 ms^{-1} till a velocity is reached at which the projectile perforates the target, defining the ballistic limit. Table A1 below lists a typical input for a projectile of mass 12.5 g and diameter 7.5 mm and using material L12. The output is given at Table A2 with an explanation of symbols and then the program is listed.

Table A1 Listing of Input Data File LIMP.DAT

Parameter	Symbol in Text	Symbol in Program	Value	Units
Density	ρ	RO	2380.	kg m^{-3}
Strength	σ_1	SOK1	13335.	MPa
Exponent	n_1	EX1	0.82	-
Strain Constant	ϵ_o	EO	0.05	-
Strength	σ_2	SOK2	2240.	-
Exponent	η_2	EX2	0.214	-
Shear Stress	τ_s	SS	166.	MPa
Fibre Stress	σ_F	BSG	433.	MPa
Ultimate Stress	σ_u	AB	9.	(^{o})
Critical Bend Angle	θ_c	TS	503.	MPa
Thickness	h_o	HO	.0082	m
No of Layers	n	NO	6	-
Projectile Mass	m	ASS	.0127	kg
Projectile Diameter	D	DIAM	.0075	m

Table A2* **Listing of Output File - LOMP.DAT**

BA	CL	HT	STRN	WK	W	VN	V	T
.0013	.0069	.0075	0.089	56.6	87.3	204.5	203.7	.00594

THROUGH

W	WP	VR	LNE	LT	LB
357.7	270.4	41.6	5	2	3

EN
350.7

VO=BALLISTIC LIMIT
235.0
AREAL DENSITY KG/M2
19.52
TOTAL THICKNESS MM
8.20
NO. LAYERS
6
LAYER THICKNESS MM
1.367

Symbols : (BA,CL,HT) = (L_B, L_C,h) See Figure 2.
STRN, Uniaxial Strain in plug.
WK, Compressive Work Stage I (W_N in text).
W, First Line - Total Work Stage I, Second Line - Total Work of Perforation.
VN, V Plug Velocity at end of Stage I, Projectile Velocity at End of Stage I.
T, time of first stage.
VR, residual velocity after perforation.
LNE, Total layers to be perforated in Stage II.
(LT,LB) = (n_1, n_2) See text.
EN, projectile initial kinetic energy.

LISTING OF PROGRAM LAMP

```
C   LAMP.FOR
C   PROGRAM TO CALCULATE PENETRATION PARAMETERS FOR
    MULTI-LAYER
C   COMPOSITE TARGETS  R.L.WOODWARD AND I.G.CROUCH,DSTO
C   MATERIALS RESEARCH LABORATORY,1988.
    OPEN(UNIT=1,FILE='LIMP',STATUS='OLD')
    OPEN(UNIT=2,FILE='LOMP',STATUS='NEW')
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21  FORMAT(F5.0/F6.1/F5.3/F8.5/F6.1/F5.3/F6.1/F6.1/F5.2/F6.1
    1/F7.4/I4/F7.6/F7.6)
    READ(1,21)RO,SOK1,EX1,EO,SOK2,EX2,SS,BSG,AB,TS,HO,NO,ASS,DIAM
75  FORMAT(T4,'BA'T11,'CL'T18,'HT'T25,'STRN'T33,'WK'T44,'W'
    2T55,'VN'T64,'V'T72,'T'T80)
    WRITE(2,75)
76  FORMAT(4X,F10.1,4X,F10.1,4X,F10.1,4X,I3,4X,I3,8X,I3)
77  FORMAT(2X,F5.4,2X,F5.4,2X,F5.4,2X,F6.3,2X,F6.1,5X,F6.1,
    35X,F5.1,2X,F7.1,1X,F6.5)
78  FORMAT(T3,'THROUGH')
86  FORMAT(T7,'W'T22,'WG'T38,'VR'T47,'LNE')
87  FORMAT(T7,'W'T22,'WP'T38,'VR'T47,'LNE'T55,'LT'T65,'LB')
88  FORMAT(T7,'EN'T20,'VO=BALLISTIC LIMIT')
79  FORMAT(2X,F10.1,10X,F6.1)
51  FORMAT(T20,'AREAL DENSITY KG/M2')
52  FORMAT(22X,F10.2)
53  FORMAT(T20,'TOTAL THICHNESS MM')
54  FORMAT(22X,F8.2)
55  FORMAT(T20,'NO. LAYERS')
56  FORMAT(22X,I3)
57  FORMAT(T20,'LAYER THICKNESS MM')
58  FORMAT(22X,F8.3)
    SOK1=SOK1*1000000.
    SOK2=SOK2*1000000.
    SS=SS*1000000.
    BSG=BSG*1000000.
    AB=.008727*AB
    TS=TS*1000000.
    TL=HO/NO
    ARED=RO*HO
    HOMM=HO*1000.
    TLMM=TL*1000.
    RAD=DIAM/2.
    B1=((SOK1*EX1/RO)**.5)*2/(EX1+1)
    B2=((SOK2*EX2/RO)**.5)*2/(EX2+1)
    VOL=3.1416*RAD**2*HO
    VO=10.
    DVO=5.
C   START VEL. INCREMENTING IN 5 M/S STEPS TO GET BALL. LIMIT
    DO 207 M=1,300
    EN=.5*ASS*(VO**2)
    ST=.001
    STRN=.001
    WK=0
    BA=0
C   START FIRST STAGE - PLUG ACCELERATION
    DO 102 L=1,5000
    IF(STRN.GE.EO)GO TO 33
    VN=B1*STRN**((EX1+1)/2)
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```
      F=VOL*SOK1*(STRN**EX1)/HO
      GO TO 34
   33 VN=B1*EO**((EX1+1)/2)+B2*STRN**((EX2+1)/2)-B2*EO**((EX2+1)/2)
      F=VOL*SOK2*(STRN**EX2)/HO
   34 HT=HO*EXP(-STRN)
      T=(HO-HT)*2/VO
      FR=VN*T/2
      BA1=(VO+VN)*T/2
      DBA=BA1-BA
      BA=BA1
      CL=HO-BA
      WK=WK+F*DBA
      WS=3.14159*RAD*SS*(HT*(HO-HT)+FR*(2*HT-FR))
      WF=(3.14159*SS*RAD*BA**2)
      W=WS+WF+WK
      V2=VO**2-2*W/ASS
      IF(V2.LT.0.)GO TO 206
      V=V2**.5
      T=T*1000
      IF(V.LE.VN)GO TO 99
      IF(CL.LE.0)GO TO 100
      STRN=STRN+ST
  102 CONTINUE
C     BEGIN SECOND STAGE - DISHING
   99 LNI=1.+BA/TL
      TE=HO-(LNI*TL)
      LNE=NO-LNI
      SASS=ASS+3.1416*(RAD**2)*HT*RO
      RKE=0.5*SASS*(VN**2)
      WT=.3927*(DIAM**2)*HT*TS
      IF(AB.LT..004)GO TO 308
      AB=AB*((HO/TE)**2)
      IF(AB.LT.1.5708)GO TO 306
      AB=1.5708
C     WORK-GOOD BONDING
  306 WBG=.7853*DIAM*(TE**2)*BSG*AB
      LT=LNE/2
      LTD=2*LT
      IF(LTD.EQ.LNE)GO TO 204
      LB=LT+1
      TT=TL*LT
      TB=TL*LB
      GO TO 205
  204 LB=LT
      TT=LT*TL
      TB=TT
C     WORK-LAMINATE BOND BROKEN
  205 WBP=.7853*DIAM*BSG*((TT**2)+(TB**2))*(1.5708-AB)
      GO TO 320
```

```
C    WORK-NO INTERLAMINAR BONDING
308  WBN=1.2335*DIAM*BSG*(TE**2)/LNE
320  W2=W+WT+WBG+WBP+WBN
     WP=WT+WBG+WBP+WBN
     V2=VN**2-2*WP/SASS
     IF(V2.LT.0.)GO TO 206
     VR=SQRT(V2)
     WRITE(2,77)BA,CL,HT,STRN,WK,W,VN,V,T
     WRITE(2,78)
     WRITE(2,87)
     WRITE(2,76)W2,WP,VR,LNE,LT,LB
     GO TO 350
206  VO=VO+DVO
207  CONTINUE
100  WRITE(2,101)
101  FORMAT(T3,'CL=0   OR  OUT OF TIME')
350  WRITE(2,88)
     WRITE(2,79)EN,VO
     WRITE(2,51)
     WRITE(2,52)ARED
     WRITE(2,53)
     WRITE(2,54)HOMM
     WRITE(2,55)
     WRITE(2,56)NO
     WRITE(2,57)
     WRITE(2,58)TLMM
     STOP
     END
```

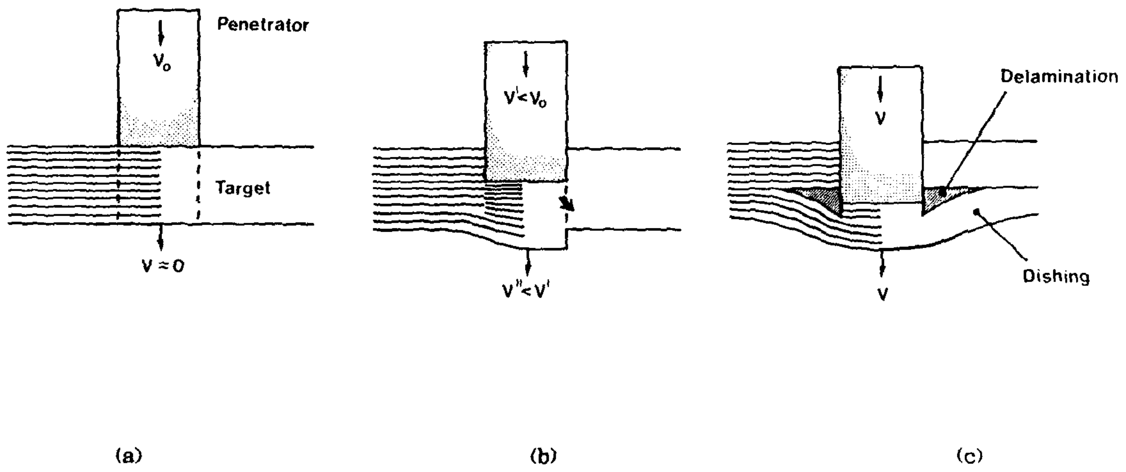


Figure 1 *Schematic of the perforation process in a laminated target.*

(a) The initial impact conditions,

(b) Stage I where the projectile moves faster than the target plate material in front, so that compressive deformation of the target material occurs as well as shearing between the material ahead of the projectile and the rest of the target.

(c) Stage II when the projectile and "plug" are moving at the same velocity, delamination of unsheared laminae at the back of the target occurs and deceleration is affected by resistance of the dishing target material.

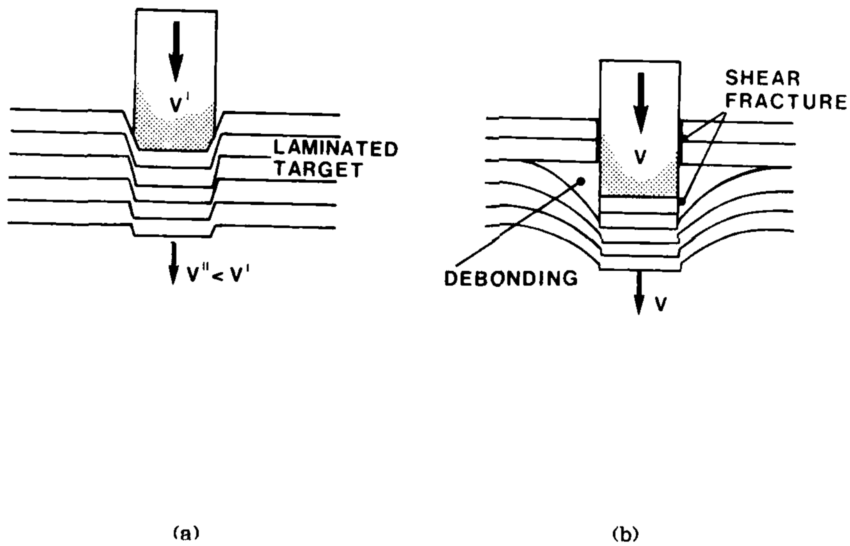
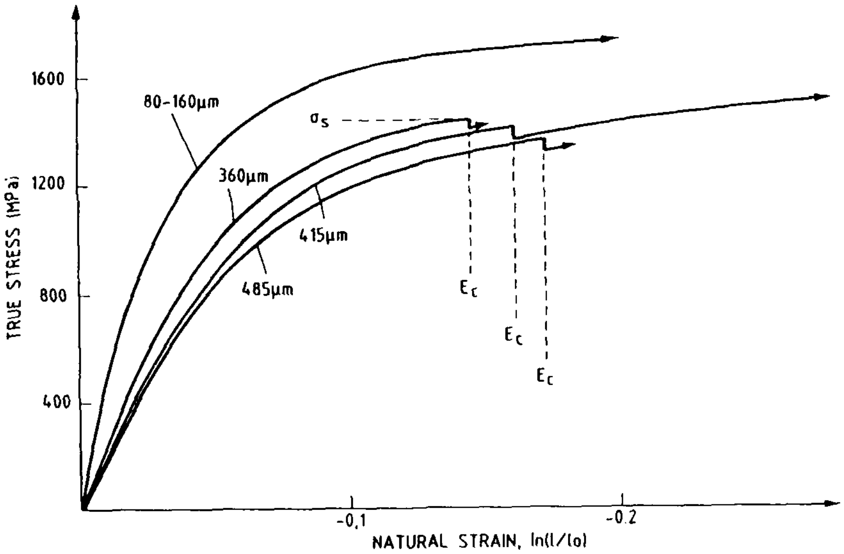
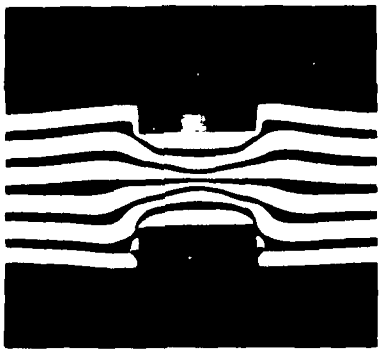


Figure 2 (a) *The deformation of a laminated target at the end of Stage I, where L_B defines the position of the back of the plug or front of the projectile. The material to be dished in Stage II is determined by the next interface below the projectile position, thickness T_E. Other symbols relate the deformation to that of a homogeneous target [1].*

(b) *Deformation of the laminate in Stage II showing the debonding and those laminae which have failed by shearing.*



(a)



(b)

Figure 3 (a) *Typical uniaxial stress/uniaxial strain data for 6-ply 7075 aluminium alloy laminates of varying adhesive thickness from constrained compression tests.*

(b) *Sample of a 6-ply 7075 aluminium alloy laminate plate which has been compressed between flat dies in a constrained compression test showing the typical strain distribution and the radial extrusion of material against the constraint provided by the surrounding plate.*

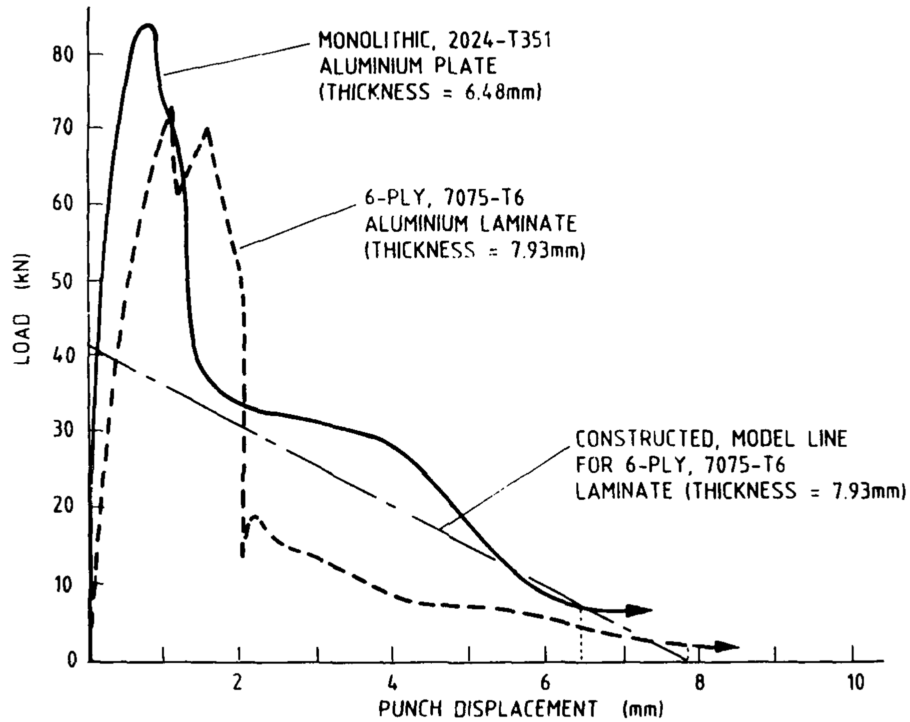


Figure 4 *Load/displacement test data for monolithic and laminated samples showing the construction of a line to define the shear strength of the laminate using the area under the load displacement curve for the laminate and its through thickness as fixed parameters.*

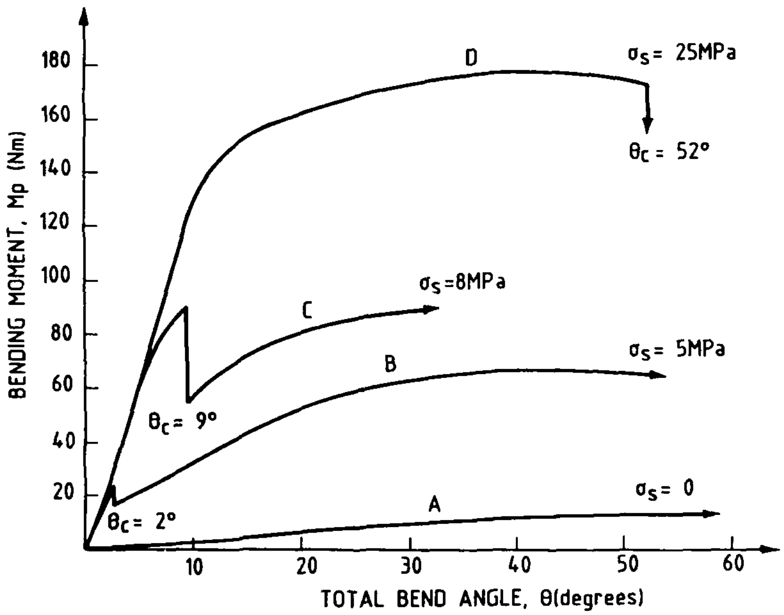


Figure 5 *Typical moment/angle of bend data for laminates: A - unbonded, B & C - poorly bonded and D - well bonded - the interlamellar shear strengths measured are indicated and failure in shear by a sudden drop in bending moment at the indicated angles.*

(a)

(b)

(c)

Figure 6 *Typical sections from laminates of*

(a) 2090 aluminium alloy showing brittle behaviour
(b) 2024 and
(c) 7075 aluminium alloys.

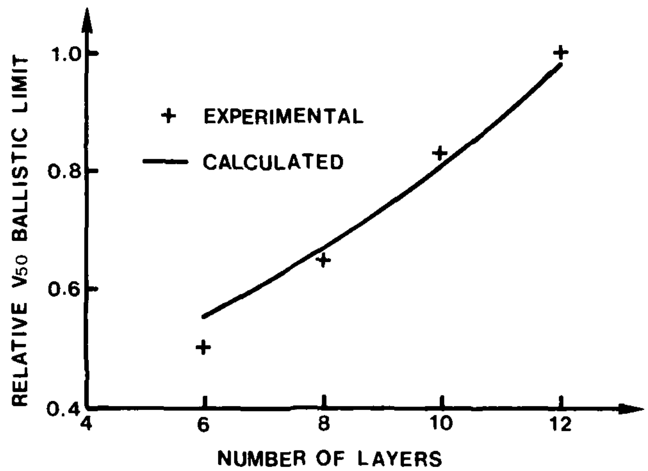


Figure 7 *Comparison of model calculations and experiment (10) for 7.5 mm fragment simulating projectiles impacting laminates of varying thickness.*

SYMBOLS

C	Longitudinal wave speed
D	Projectile diameter
F	Force
h_o, L	Laminate initial thickness, plug thickness after acceleration
L_B, L_F	Displacement of back (impact side), and front of plug respectively
M_p	Bending moment measured in four point bend test
m	Projectile mass
n	Number of layers in laminate, number of layers to be penetrated in Stage II
n_1, n_2	Numbers of layers in two sections following bond failure in Stage II
T_E	Thickness of laminate to be perforated in Stage II
T_L	Thickness of one layer of laminate
t	Time
V_1, V_o, V_p	Velocity of plug after acceleration, of projectile after deceleration, and impact velocity respectively
v	Velocity
W, W_N, W_S, W_F, W_B, W_T	Work, Work done in plug compression, Work of shear, Work of friction, Work of bending and Work of tensile deformations respectively
w	Width of sample in four point bend test
Y	Yield stress
σ, σ_u, σ_F	Stress, ultimate stress, fibre stress respectively
σ_1, σ_2	Curve fitting parameters, including combined effect of flow stress and constraint, equations (1)

ϵ, ϵ_o	**Strain and strain constant curve fitting parameter for equations (1)**
ρ	**Density**
τ_s	**Shear flow stress**
θ, θ_c	**Angle of bend, critical angle of bend for bend failure in four point bend test**
η_1, η_2	**Curve fitting parameters for work hardening exponent, equation (1)**

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TITLE

A computational model of the perforation of multi layer metallic laminates

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ABSTRACT

A model for the deformation of multi-layer metallic laminate targets during ballistic impact is described. The model divides the process into a stage of plug acceleration followed by dishing of the rear of the target, and allows for the effects of variable interlamellar bend strength. A computational procedure is described, as well as the mechanical test procedures to generate the input data for the program. Examples of the application of the model are described to illustrate the interpretation of results, the limitations of the model, and the use of the model is parametric studies for laminate design. The computer program is listed with typical input and output data.

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